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Developing indicators to identify coastal green infrastructure potential: The case of the Salish Sea region

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ABSTRACT

This study investigates where coastal green infrastructure (CGI) can provide highest potential coastal protection benefits, while considering its vulnerability to environmental conditions. CGI provides important coastal protection benefits, however, influenced by climate change and human activities, these benefits are highly threatened. This vulnerability of CGI was not considered in the previous studies. This study provides a framework and an indicator-based methodology to fill this gap. A review of the literature was conducted to identify the parameters used to measure CGI's coastal protection benefits and vulnerability. The content of the references that contained specific parameters related to CGI's role in coastal protection and vulnerability were systematically reviewed. A total of 11 indicators were identified and organized into two indices: CGI coastal protection index, and CGI vulnerability index. The indices were synthesized using a 2 × 2 matrix to identify areas with the highest coastal protection potential. Analysis was conducted for the 74 most populated coastal communities in the Salish Sea region. Results indicate that the British Columbia communities in the Salish Sea region have high potential to utilize CGI for coastal protection. CGI in 59% of the communities in British Columbia and 36% in Washington State can provide high coastal protection benefits, even when vulnerability is accounted for.

1. Introduction

Traditionally, coastal adaptation to climate change has prioritized the protection of coasts using hard structures such as dikes, seawalls, spillways, groins, and other built structures (Klein et al., 2001; Airoldi et al., 2005; Renaud et al., 2013; Feagin et al., 2015; Schubert et al., 2017). However, there has been a growing debate on coastal protection roles and benefits of hard structures, as well as their environmental, social and economic implications (Sutton-Grier et al., 2015).

These human-made structures are static and unable to respond to changing conditions such as urban sprawl, climate change, and new planning and engineering regulations (McGranahan et al., 2007; Borsje et al., 2011). They are often expensive to build, and they require regular maintenance (Temmerman et al., 2013; Onuma and Tsuge, 2018). They provide an inflated sense of protection and security, resulting in increases in development in flood-prone areas (Tyler, 2016; Schubert et al., 2017). Moreover, they cause significant damages to ecosystems and sensitive habitats by disrupting natural processes and preventing migration of habitat and species along to the coastal profile (Hanley et al., 2014; Onuma and Tsuge, 2018; Sutton-Grier et al., 2018). Consequently, they may have adverse implications for the coastal tourism sector, and local and regional fisheries (Onuma and Tsuge, 2018). In addition, parts of these hard structures can become loose with strong wave activity or through time and can cause significant damages to infrastructure, assets, and human lives (Sutton-Grier et al., 2018; Tyler, 2016). These unwanted effects of traditional hard structures (THSs) have led to growing recognition of the need for dynamic, safe and multi-functional ways of coastal protection (Cheong et al., 2013; Temmerman et al., 2013; The Horinko Group, 2015; Narayan et al., 2016; Sutton-Grier et al., 2018).

In response, the role of coastal green infrastructure (CGI), natural or nature-based systems that provide coastal flood and erosion protection as well as multiple social, economic and environmental benefits, have started to gain attention (Gedan et al., 2010; Arkema et al., 2017; Sutton-Grier et al., 2018). Studies of Coops et al. (1996); Mol (2003); Feagin et al. (2005, 2009); Koch et al. (2009); Borsje et al. (2011); Anderson and Smith (2014); Möller et al. (2014); Spalding et al. (2014); Wu and Cox (2015); Narayan et al. (2016); Ruckelshaus et al. (2016) and others indicate that CGI is an effective practice of protecting coasts from flooding and erosion. Although these studies did not use the CGI terminology, their research concluded that CGI practices protect coasts from flooding through reducing the wave energy by drag friction,

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reducing wave overtopping by eliminating vertical barriers, and absorbing floodwaters in soil (The Horinko Group, 2015; Ruckelshaus et al., 2016; Narayan et al., 2016; Arkema et al., 2017); and from erosion through reducing wave transmission, increasing soil elevation through vertical accretion and binding soil properties (Shepard et al., 2011; Hettiarachchi et al., 2013; Spalding et al., 2014; The Horinko Group, 2015; Silva et al., 2016b). Besides its coastal protection benefits, CGI enhances natural coastal processes, sequesters carbon, provides habitat for wildlife, increases economic activities such as fishing and tourism, creates recreation opportunities, and improves aesthetics of coastal communities (Davidson-Arnott, 2010; R et al., 2010; Barbier et al., 2011; Barnhill and Smardon, 2012; Sutton-Grier et al., 2014, 2015).

Although CGI is now widely recognized for its value in coastal protection and providing various other benefits, it is also considered to be vulnerable to changes in the environments they interact with (Osland et al., 2015). For example, changes in the land use, water levels, and storm intensities and frequencies can have significant implications on the health and integrity of CGIs and the services they provide (Khattabi and Bellaghmouch, 2009). Therefore, CGI's coastal protection benefits are not solely affected by the physical characteristics of and changes in the natural and built environments, and the intensity of the hazards they are exposed to. CGIs adaptability to these changes can also significantly affect their coastal protection benefits. Especially with climate change, and the associated increases in the global sea levels and acceleration of storm intensities and frequencies, the vulnerability of CGI can potentially reduce, if not eliminate, its coastal protection benefits (Duarte et al., 2013; Langridge et al., 2014; Osland et al., 2015).

Hence, the type and extent of benefits acquired from CGI depend on the location it is implemented in (Ruckelshaus et al., 2016). This is because CGI and its interactions with coastal processes and built environments are context-depended (Hanley et al., 2014) and vary spatially and temporally (Koch et al., 2009; Barbier et al., 2011; Feagin et al., 2015). Yet, despite this place-specific dependency, identifying where to utilize CGI in coastal areas has been largely absent from the literature (Ruckelshaus et al., 2016). Filling this gap entails understanding where along the coasts CGI can provide protection benefits, and where it is likely to be vulnerable to changing environmental conditions. Considering CGI vulnerability while identifying coastal areas with the highest potential CGI protection benefits is important because it allows for prioritizing restoration efforts and new CGI implementation. Such an approach can also make it easier for local and regional level governments to allocate funds and other resources to areas with the highest potential for CGI benefits.

Therefore, this study aims to answer the following research questions. What parameters can be used to identify CGI coastal protection benefits and vulnerability? What criteria can be used to organize these parameters into CGI coastal protection and vulnerability indices? How can these indices inform where CGI has greater (or lesser) promise for coastal protection on the basis of the degree of potential coastal protection benefits and the degree of vulnerability? The study uses the Salish Sea region as a case study area to demonstrate the methods of this research.

The paper is organized as follows. Section 2 provides a literature review of CGI, its coastal protection benefits, and vulnerability. Section 3 describes the study area. Section 4 explains the methodological approach of this study. Section 5 provides and explains the results. Section 6 discusses the implications of the findings and the limitations of the methodology. Section 7 offers concluding remarks.

2. Coastal green infrastructure (CGI)

The green infrastructure terminology has been used by natural resource professionals (i.e., coastal zone management (Cooper and McKenna, 2008)), planners, and engineers in the last 40 years (Liquete et al., 2015). There are three main groups of green infrastructure: urban green infrastructure, which deals mainly with water and stormwater management in urban areas; watershed-based green infrastructure, which protects, fosters and connects networks of green spaces and forests; and coastal green infrastructure, which refers to the practices that aim to deal with flooding and erosion (The Horinko Group, 2015). This study focuses solely on the coastal green infrastructure (CGI).

Although CGI is a growing practice, its definition is not uniformly accepted and depends on the context that is studied. Some of the most common definitions are the following.

Benedict and McMahon's definition of CGI was “an interconnected network of natural areas and other open spaces that, (…), provides a wide array of benefits to people and wildlife” (2006, pg.1). Tzoulas defined CGI as “all natural, semi-natural and artificial networks of multi-functional ecological systems, (…), at all spatial scales” (2007, pg.1). Edwards et al. (2013) uses the term “blue infrastructure” to define coastal and riparian habitats that maintain coastal processes and ecological functions, and provide various ecosystem services. The European Commission (2013) defines CGI as natural and semi-natural areas that are strategically planned, designed and managed to provide various ecosystem services. The Conservation Leadership Council's 2015 report refers to CGIs as “nature-based systems and processes” (2015, pg.1). The Environmental Protection Agency (USEPA, 2015) and the US Army Corps of Engineers (Bridges et al., 2015) in the USA define CGI as natural areas and processes, or nature-based (designed and engineered) systems that mimic natural processes that provide coastal protection, habitat and other services. Recently, Soz et al. defined CGI as an approach that uses natural processes to manage flooding while providing other ecosystem services (2016, pg. 1). Narayan et al. uses the term “nature-based defenses” and defines it as “existing coastal habitats within which wave reduction has been measured” (2016, pg.1).

Driven from these definitions, CGI in this study refers to natural or nature-based systems that mimic natural areas of dynamic coastal landforms, vegetation, and reefs that naturally provide coastal protection services as well as various ecosystem health, maintenance of natural processes and biodiversity, and social and economic benefits to communities.

Common types of CGI are: (1) dynamic coastal landforms such as sand/gravel/rocky beaches, barrier islands, and dunes (Barbier et al., 2011; Sutton-Grier et al., 2015; Ruckelshaus et al., 2016), including beach nourishment practices (Brown et al., 2016); (2) coastal vegetation such as mangroves, eelgrasses, dune vegetation, salt marshes and kelp forests (Davidson-Arnott, 2010; Arkema et al., 2013; Duarte et al., 2013; Sutton-Grier et al., 2015; The Horinko Group, 2015; Ruckelshaus et al., 2016); and (3) reef systems such as mussel beds, oyster reefs and coral reefs (Gutiérrez et al., 2011; Cheong et al., 2013; Sutton-Grier et al., 2015; Ruckelshaus et al., 2016).

2.1. CGI coastal protection benefits

CGI's coastal protection benefits are mainly two-fold: flood protection and erosion protection. CGI protects coastal areas from flooding by reducing the fetch for the wind to form waves, absorbing wave energy through surface roughness and drag friction, leading to a reduction in wave height and velocity, and absorbing floodwaters through permeable natural or engineered surfaces (Davidson-Arnott, 2010; Cheong et al., 2013; Spalding et al., 2014). Erosion protection is achieved by maintaining or increasing surface elevation by trapping sediments and build-up from decaying vegetation on soil, and binding soil particles through vegetation roots (Barbier et al., 2011; Bryant et al., 2017).

2.1.1. Flood protection

Fonseca and Cahalan (1992) studied seagrasses and their role in reducing wave energy over a one-meter test section. They concluded that the percentage of average wave reduction by four species of

seagrasses was approximately 40% and wave energy reduction was significantly cut when water depths become higher or equal to twice the mean leaf length. Coops et al. (1996) found that through a 4 m wide profile of wave tank, wave heights over areas without salt marshes ranged from 71% to 129% more of the height of waves for areas with salt marshes. Möller et al. (2001) found that salt marshes reduced wave heights in all observations at rates 27%–98%. They also found that the total energy dissipation rates were on average 82% over salt marshes compared to on average 29% on sand flats. In another study Möller and Spencer (2002) suggested that on average 92% wave height attenuation was obtained over a 310 m coastal profile of salt marshes, and the first 10 m of the canopy provided the most rapid reduction in wave height. Later, Möller (2006) suggested that salt marshes could effectively reduce up to 33% of wave height over a 10 m coastal profile, depending on the salt marsh canopy height and density, and water depth conditions.

Loder et al. (2009) used numerical models for their study and found that a 400-km^2 salt marsh area is effective to reduce less than 2 m of storm surge (35%–70% surge decrease). Bradley and Houser (2009) concluded that over a one m water depth range, wave heights decreased on average by 30% after the first 5 m over 39 m, and decreased exponentially over the remainder of the bed. Similarly, Koftis et al. (2013) suggested a 35% reduction in wave heights by seagrasses in an extensive experimental study. Anderson and Smith (2014) suggested that artificial seagrasses attenuated the wave energy in all wave frequency conditions. John et al. (2015) suggested an exponential reduction in wave height over a 50 m long wave flume of submerged artificial seagrass vegetation. Jeanson et al. (2016) conducted a field experiment to measure the wave energy dissipation over shallow submerged coral reefs and suggested an average energy reduction of 91.5% between the fore-reef and back-reef. Silva et al. (2016a) investigated the role of the vegetated dune systems using wave flume experiment and concluded that dune vegetation prevented wave over-wash as well as dune erosion.

Studies after Hurricane Katrina and the Indian Ocean Tsunami suggested that presence of wetlands and mangroves reduced the infrastructure damage, injuries and fatalities caused by extreme events (Chang et al., 2006; Barbier et al., 2013). Supporting the above-mentioned studies, Narayan et al. (2016) meta-analyses of CGI's wave reduction suggested that CGIs play significant roles in reducing wave heights, on average 35% and 71% reduction in wave heights, and the extent of coastal protection achieved varies with the location and conditions of each location.

2.1.2. Erosion protection

CGI reduces erosion directly by reducing wave transmission, capturing sediments and indirectly through stabilizing soil properties (Feagin et al., 2009; Silva et al., 2016b; Bryant et al., 2017; Mendoza et al., 2017). Coops et al. (1996) suggested that different types of CGI reduced erosion at different rates. Examining different types of salt marshes, they noted that *P. australis* salt marshes showed higher aboveground biomass and reduced erosion by 82%, while *S. lucustris* salt marshes reduced only 33%, compared to not vegetated areas. Piazza et al. (2005) found that coastal erosion was $0.08 \pm 0.02m$/month at oyster reef present sites as compared to $0.12 \pm 0.01m$/month at oyster reef absent sites. In another study area, Scyphers et al. (2011) found that oyster reefs successfully mitigated erosion by more than 40% over two years. Levin et al. (2007) suggested that the sand deposition, thus accumulation, was much higher in areas with taller coastal vegetation, compared to shorter vegetation.

More recently, in a study investigating the dune erosion, Kobayashi et al. (2013) concluded that wooden dowels and wide dune vegetation reduced the dune erosion by decreasing the wave overtopping and overwash rates. In a large-scale implementation and monitoring study, Stive et al. (2013) suggested that sand nourishment will increase the width of the beach and will increase the beach area approximately 200 ha in 20 years after implementation. In physical model experiments on the effects of vegetation on dune erosion, Figlus et al. (2014) suggested that the vegetation reduces eroded dune volumes and concluded that the vegetation root maturity plays a significant role on reducing erosion. Martinez et al. (2016) found that vegetation effectively reduces coastal erosion in three different storm conditions, through 24 experiments of two coastal profiles. Silva et al. (2016b) investigated the role of vegetation cover on the sediment movement along two coastal profiles and concluded that vegetation reduces net coastal erosion regardless of different wave and morphological conditions, and prevents shoreline retreat. Borsje et al. (2017) suggested that coastal erosion can be prevented and functions of the coastal areas and processes can be maintained with beach nourishment. Mendoza et al. (2017) stated that vegetation effectively contributes to the resistance of the coastal profile during storms through trapping sediments and strengthening soil.

2.2. CGI vulnerability

There is now numerous evidence on CGI's role in coastal protection (Arkema et al., 2017). At the same time, there is a growing interest in using CGI for coastal protection (Ruckelshaus et al., 2016). It is recognized that CGI's coastal protection benefits can vary depending on the context in which they are utilized (Koch et al., 2009). It is also recognized that CGI itself can be vulnerable depending on the context it is located in, and the rate and magnitude of the environmental changes in that environment become too high for CGI to adapt to. Thus, this vulnerability can lessen CGI coastal protection benefits.

In the past 50 years, around 25%–50% of the coastal areas with essential landforms, vegetations, and reef systems have been lost globally due to changing environmental conditions such as increased pollution, changes in coastal land use, and climate change (Duarte et al., 2013; Feagin et al., 2015). Notably, the impacts of climate change such as increased frequency, duration and intensity of storms, and rising sea levels have intensified the hazards CGI is exposed to (Johnson et al., 2012; Ghosh, 2015). However, CGI has response mechanisms such as accretion or migrating along the coast to deal with these hazards (Feagin et al., 2015). What makes CGI vulnerable, however, are the external interventions that disable these response mechanisms. These interventions are often in the form of extensive occupation of coastal areas, where CGI has no or insufficient physical space to move and adjust ('coastal squeeze') (Feagin et al., 2005; Osland et al., 2015; Kirwan et al., 2016); construction of human-made structures or human activities that intervene with the natural sediment flow to the coasts (Feagin et al., 2010); or rapid acceleration of sea level rise due to climate change, or local water levels due to engineering activities that change coastal profile (Duarte et al., 2013).

Feagin et al. (2005), investigated the vulnerability of dune vegetation to rising sea levels in a spatial model on Galveston Island, Texas, USA. The study concluded that in the low sea level rise scenario (0.09 m by 2100), dune vegetation was able to fully developed and cope with the increase in the sea levels. However, in the high sea level rise scenario (0.88 m by 2100), only a thin strip of dune vegetation was developed due to high stressor level. Moreover, in the high-rise scenario, the thin dune vegetation was neither able to block winds nor accumulate new soil layers. Feagin et al. (2005) also stressed that human developments along the coasts which restrict migration of CGI landwards are key determinants of vulnerability. Khattabi and Bellaghmouch (2009) found in a simulation study that with a 0.5 m sea level rise a loss of 478.7 ha and with a 2 m sea level rise a loss of 1400 ha may be observed by 2100 in a wetland in the North East coastal zone of Morocco.

Similarly, Kirwan and Temmerman (2009) and Kirwan et al. (2010), investigated CGI's surface accumulation while facing sea level rise in modeling studies. Their results concluded that at sea level rise rates more than 20 mm per year; salt marshes in medium to high tidal ranges and sediment concentrations survive, while salt marshes in low tidal ranges and sediment concentrations fully submerge. They suggested that full submergence occurs approximately 30–40 years after the threshold sea level rise rates are

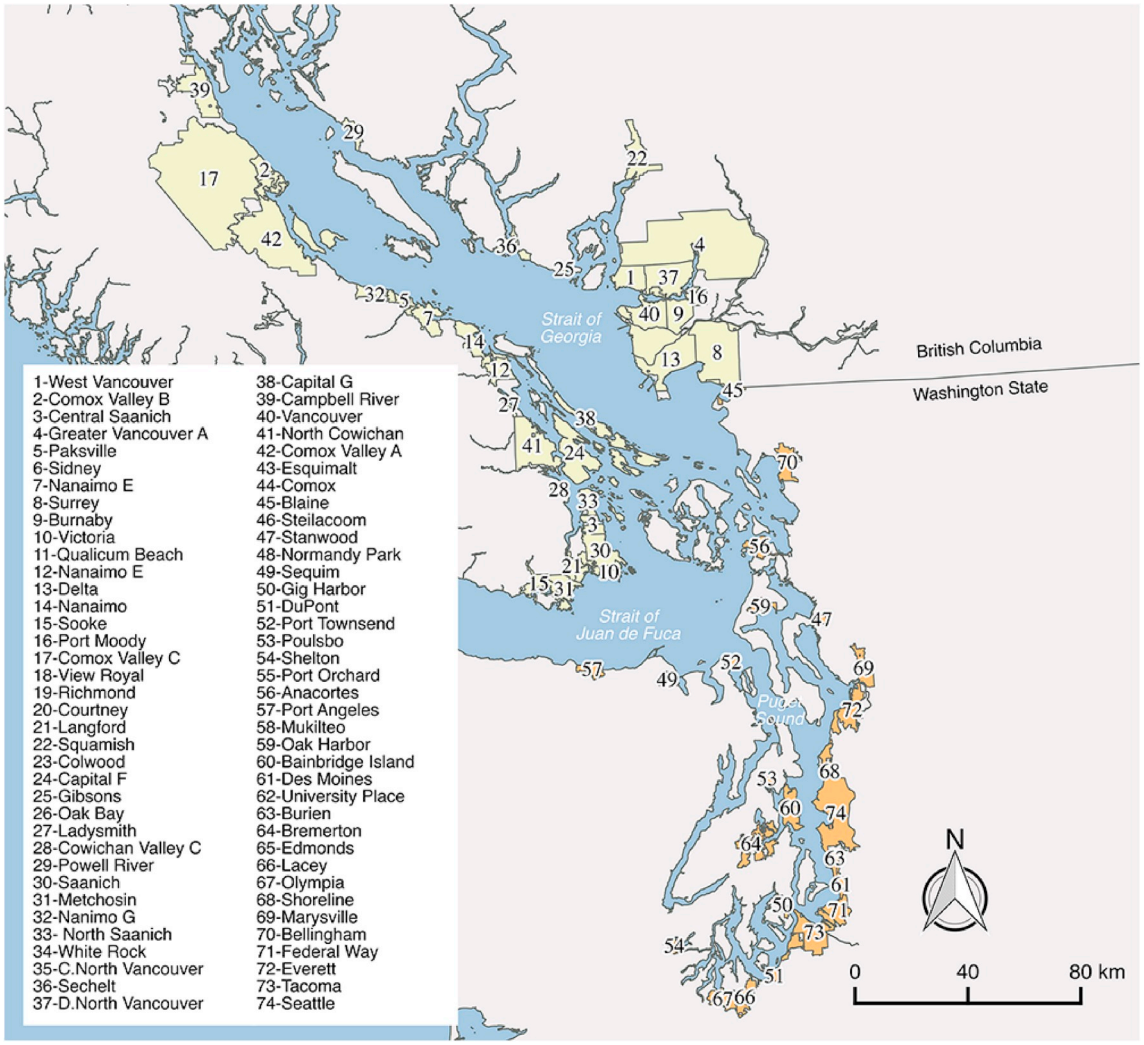

Fig. 1. The Salish Sea and the study area communities.

exceeded. Later, Kirwan et al. (2016) suggested a threshold rate of 10–50 mm/yr for the relative sea level rise and marsh survival, and vegetation areas with less than 1 m tidal range and less than 20 mg/L sediment concentrations will be vulnerable to even the moderate rate of sea level rise. Kirwan et al. (2016) also suggested that gently sloping coastal profile enhances and fosters marsh expansion. They stated that even at high sea level rise rates, marsh survival could be achieved, only if the vegetation is able to migrate inland and is not limited by natural or human-made barriers.

Thorne et al. (2013) investigated the ability of a 309 ha tidal marsh area to increase its surface elevation over 13 years to keep up with the rising water levels using two elevation surveys. Their result concluded that 63% of the area did not accrete at a rate that exceeded SLR, thus subsided. They also stated that the long distance to sediment source was the most significant factor in the lack of accretion. Mariotti and Carr (2014) also supported previous findings, stating vegetation is likely to drown when sea level rise is fast, and access to sediment is low. They suggested a 0.3 (mm/yr)/(mg/L) ratio of sea level rise and sediment concentration is a threshold for vegetation drowning, and at least 50 mg/L sediment concentration would be needed to prevent vegetation retreat even in cases where sea levels are stable.

Literature shows that the extent of CGI benefits varies significantly depending on the geomorphological, wave and CGI related characteristics of their environment. Similarly, the degree of CGI vulnerability differs depending on the geomorphological, land use and CGI related characteristics as well as environmental change types and rates.

3. Study area

The Salish Sea region is selected to identify areas with highest potential CGI. The Salish Sea is a body of water that encompasses the south of British Columbia in Canada and north of Washington State in the United States. The area includes the Strait of Georgia, the Puget Sound (PS), and the Strait of Juan de Fuca (Fig. 1). The Salish Sea is an inland body of water, mostly protected from the large wave and wind events of the Pacific Ocean.

The Salish Sea region is an important international body of water that is home to many coastal communities with diverse economic, and built and natural environment characteristics. The coastal communities of the Salish Sea range from small towns with only a few hundred residents and single sector economy, to large metropolitan areas such as Vancouver and Seattle with complex economies. The coasts range from low-lying sand flats to coasts with cliffs, from salt marsh fields to dunes and rocky beaches. The variation of the characteristics of Salish Sea communities provides a diverse setting for this study and demonstrates the spatial variation in CGI benefits and vulnerability in the region.

Coastal communities with populations over 4000 were identified from both British Columbia and Washington State. 44 Coastal communities from British Columbia and 30 coastal communities from Washington State were selected for this study. The unit of analysis of this regional level study is the Canadian Census Subdivision (CSD) units for British Columbia communities, which is the equivalent to a municipality, and the American Census City/Urban Growth Areas (UGA) for the Washington State communities, which is

the incorporated city boundaries and unincorporated Urban Growth Areas. These units are comparable, and publicly accessible data are available for both geographic units in the federal and provincial/state databases.

Besides its importance and diversity, the Salish Sea region is an important area for this study because the governments and communities in this region have a high level of interest in CGI projects. Particularly in Washington State, numerous county governments (i.e., Skagit County, Snohomish County, King County, etc.), multi-organizational partnerships (i.e., Puged Sound Partnership) and environmental non-profits (i.e., Northwest Straits Foundation) have been initiating projects that remove human-made structures such as bulkheads and restore habitats and beaches. Besides, already several important CGI initiatives such as Green Shores BC and Green Shores Program of Washington State exist in the region and educate local governments, community groups, and waterfront property owners in ways they can utilize CGI. Even though such initiatives are limited in British Columbia compared to Washington State, recent federal and provincial initiatives such as green infrastructure grant program creates an increased push for CGI projects.

4. Methods

This study uses an indicator-based approach to identify areas with the highest CGI potential in the study area. Indicator-based approaches were used, amongst others, in fields such as disaster risk reduction (i.e., Cutter et al., 2003), emergency management (i.e., Flanagan et al., 2011), sustainable development (i.e., Tanguay et al., 2010), coastal zone management (i.e., Martí et al., 2007), coastal geomorphology (i.e., Carapuço et al., 2016), and coastal processes (i.e., Óscar Ferreira et al., 2017). CGI related indicators were often used along with other social, economic and institutional indicators to assess or compare vulnerability of places (i.e., Chang et al., 2015), or along with other natural/physical indicators to assess the environmental vulnerability of coastal communities (i.e., Shaw et al., 1998; Gornitz and Kanciruk, 1989; Tibbetts and van Proosdij, 2013).

Using the indicator-based approaches for understanding CGI's coastal protection benefits and vulnerability is relatively new in the CGI research as studies are typically field studies or lab experiments. This approach has been mainly applied in cost-benefit analyses of CGIs (i.e., Narayan et al., 2016; Capotorti et al., 2017), rather than understanding coastal protection benefits of CGIs or their vulnerability to changes. However, the indicator approach provides a high-level framework that can be mapped and applied in other regions, and its findings can be easily understood and interpreted by decision-makers (Hinkel, 2011; Chang et al., 2018).

The methodology of this study comprises of the following four systematic steps: (1) literature search to identify CGI studies; (2) content analysis on the selected studies to identify parameters used in the CGI literature; (3) developing indices based on the parameters identified in Step 2 to assess CGI coastal protection benefits and vulnerability to changing environmental conditions, and mapping; and (4) synthesizing the indices developed in Step 3 into a classification system to identify areas where CGI can potentially be used as a coastal protection tool. Steps 1 and 2 address the research question "What parameters can be used to identify CGI coastal protection benefits and vulnerability?" Step 3 answers the research question "What criteria can be used to organize these parameters into CGI coastal protection and vulnerability indices?" Lastly, step 4 answers the research question "How can these indices inform where CGI has greater (or lesser) promise for coastal protection on the basis of the degree of potential coastal protection benefits and the degree of vulnerability?"

4.1. Literature review

CGI studies have used various parameters in the way they measure CGI's role in coastal protection and its vulnerability. To identify these parameters, a literature search using the Web of Science, Google scholar and Jstor databases (1970–2015, cut-off date December 2015) was conducted to target references on CGI's coastal protection benefits and vulnerability. Numerous keywords were used in the literature review. These keywords were determined through the initial review of the CGI literature and include the following: coastal protection, (coastal) green infrastructure, nature-based protection, wave attenuation, shore stabilization, flood protection, erosion protection, vegetation accretion, coastal habitats, coastal defenses, soft engineering, bioshields, and nature-based solutions.

151 primary, secondary and gray literature references matched the search criteria and were selected for review. Amongst the 151 references reviewed, 77 references were identified that contain specific parameters related to CGI's role in coastal protection and vulnerability, and therefore were selected for this study.

4.2. Content analysis

A content analysis was conducted on the 77 references to identify the parameters used to measure the CGI's role in coastal protection and its vulnerability. These parameters were recorded and coded in groups to reflect larger themes. For example, parameters related to wave height, frequency, direction, and other wave related features were grouped under 'wave characteristics' theme. Fig. 2 displays the 13 parameter themes and the frequency of use in the 77 selected CGI references.

The content analysis revealed that a large variety of parameters had been used in the CGI research. For example, Möller et al. (2001); Möller and Spencer (2002); Möller (2006); Möller et al. (2014) studies used water depth, wave characteristics, and CGI characteristics to investigate whether or not vegetation can reduce wave heights. On the other hand, Costanza et al. (2008) used CGI cover and monetary damages associated with storm surges to investigate flood protection from CGI. Similarly, Kirwan and Temmerman (2009); Kirwan et al. (2010) investigated erosion reduction rates provided by CGI through sediment concentration, sea level rise rate, tidal range, and CGI characteristics parameters; while Feagin et al. (2005, 2009) used sediment concentration, accretion, CGI characteristics, and wave/storm characteristics parameters.

As seen in Fig. 2, the most commonly used theme is the CGI characteristics. 60 out of 77 references reviewed included an indicator related to CGI characteristics. The CGI characteristics theme refers to CGI types, vegetation densities and length, surface roughness provided by different types

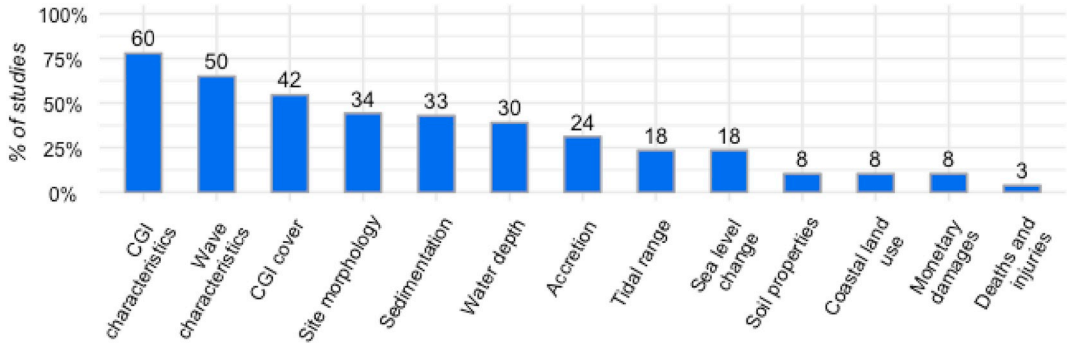

Fig. 2. Themes used to measure CGI coastal protection benefits and vulnerability.

of CGIs and other specific features of CGI. The second most used theme is the wave characteristics, which includes measures such as wave length, height, frequency, period, direction and other wave characteristics. Both the CGI characteristics and wave characteristics themes have been primarily used to determine the degree of the interaction there could be between waves and CGIs. The third indicator theme is the CGI cover. This theme refers to the area or percentage of the CGI that exists at the coast where the CGI habitat exists, or the CGI practices are implemented (i.e., beach nourishment area). This indicator theme was separated from the green infrastructure characteristics because it does not directly refer to the properties of CGI; instead, it indicates the space they cover at the coast. This theme determines the stretch of the CGI that interacts with the coastal processes.

The sedimentation theme, which indicates the sediment concentration or the amount of sediments deposited at the coast, was also commonly used in the CGI studies. They are mainly used to investigate CGI's vulnerability to changing environmental conditions because the amount of sediment deposited at coast impacts CGI's ability to accrete. Another important theme that is used in the CGI studies is the water depth. Kirwan et al. (2010), Koch et al. (2009), Möller et al. (1999, 2001); Möller and Spencer (2002); Möller (2006); Möller et al. (2014), Stone et al. (2005) and others suggested that the water depth is an important indicator for CGI's coastal protection benefit as it determines the depth CGI can interact with the wave and reduce its energy. These studies suggested that when the threshold CGI height/water depth is passed, CGI's ability to attenuate wave energy decreases because CGI can no longer interact with the waves.

Following the water depth theme is the site morphology theme such as relief, slope and type of coast (i.e., sand, gravel, and rock), and the accretion theme such as changes in soil elevation and organic decomposition. The site morphology theme is a crucial part of CGI studies since the features and position of the coasts can provide protection from wave action. The accretion theme is often used to determine the vulnerability of CGI because CGI can accrete and increase their soil elevation to keep up with the rising water levels. Commonly, the sea level change and tidal range themes were used along with the accretion theme to investigate CGI vulnerability, as the speed and rate of the sea level change and associated changes in the tidal range impact CGI's ability to accrate.

Although not used widely in the literature in the past, soil properties, coastal land use, and monetary damages themes also emerged through the literature review. The soil properties theme determines how much water can be held in the soil in occasional flooding events and the risk of erosion at the coast. The coastal land use theme is used to indicate the extent of development that needs protection, and how much space is available on the coast for green infrastructure to adapt to various water levels. The monetary damages after extreme events can also indicate the benefits CGI provides as a defense mechanism at the coast. And lastly, the damages on human lives after an extreme event can be used to measure the effectiveness of CGI.

4.3. Development of the CGI indices

4.3.1. Building the CGI database

A CGI database was created using the themes identified above. The British Columbia and Washington State databases were searched to gather publicly available data on the themes and corresponding indicators. Of the 13 themes, data were available for the following nine themes: CGI characteristics, wave characteristics, site morphology, sedimentation, water depth, accretion, tidal range, sea level change, and coastal land use. These themes, 12 correspondent indicators, and their data sources are shown in Table 1.

Data were imported as shapefiles into ArcGIS. The study area communities were extracted from the large geospatial data and data attribute tables were joined using CSD ID and UGA IDs. For each indicator, the coastal segments and corresponding data were aggregated to the unit of analysis of this study (CSDs and UGAs). The dominant features for each community were identified and recorded. Although the data for sediment concentration were available, they were incomplete; thus these data were not included in the study. The remaining 11 indicators collectively represent the composition of the coastal areas and the interaction between the landforms, built environments, and coastal processes.

4.3.2. Formatting and organizing the indices

The indicators (n = 11) from the CGI database were used to create the CGI coastal protection and vulnerability indices. First, the indicators from Table 1 were assigned to either the CGI coastal protection index and/or the CGI vulnerability index. Second, the rule-based method - if a, then b, where a is the property of an observation and b is the group it is assigned to - was applied to the indicators to rank them from very low (1) to very high (5), as shown in Table 3 and Table 4. Third, the CGI coastal protection and CGI vulnerability indices were computed. The methodology used to determine value ranges and to compute the indices was adopted from that of Gornitz and Kanciruk (1989), which combines data on indicators and ranks them from 1 to 5 to compute the "Coastal Vulnerability Index (CVI)". The CVI method is defined by Gornitz and Kanciruk (1989) as the square root of the geometric mean, divided by the total number of variables.

Table 1
CGI themes and indicators, and their data sources.

Themes	Indicator(s)	Sources
CGI charact.	- Coastal vegetation (i.e., kelp, sea grass, salt marsh, dune vegetation)	BC-PSZMS[a] and WS-SZI[b]
Wave charact.	- Wave exposure (i.e., exposed to very protected coasts)	BC-PSZMS, WS-SZI and The Geomorphology of
	- Max. wave height (m)	Puget Sound Beaches[c]
	- Max. wave fetch (km)	
Site morphology	- Relief (m)	CanCoast[d], BC-PSZMS,
	- Coastal types (i.e., estuaries, flats, beaches, cliffs, and human-made coasts)	WS-SZI, and WS Dep. of Transportation
Sedimentation	- Sediment concentration at coast. A relative index of sediment abundance (abundant, moderate and sparse) within the shore unit	BC-PSZMS and WS-SZI
Water depth	- Habitat zone (i.e., subtidal, lower tidal, intertidal, mid/high tidal, supratidal)	BC-PSZMS and WS-SZI
Accretion	- Erosion/change (m/y)	CanCoast and WS-SZI
Tidal range	- Tidal range (m)	CanCoast and WS-SZI
Sea level change	- Sea level changes (cm) in the past 100 years	CanCoast and WS Dep of Ecology[e]
Coastal land use	- Coastal land use. Green (5) to gray (1) scale referring to the use of the coast where green refers to mostly agricultural or natural uses, and gray refers to mostly commercial and infrastructure uses	DMTI Spatial Inc[f] and WS Dep. of Geography

[a] Physical Shore-Zone Mapping System for British Columbia, 2009. Average 400 m spatial resolution.
[b] The Washington State Shore Zone Inventory, 2006. Average 800 m spatial resolution.
[c] Technical Report (Finlayson et al., 2006). Based on the 30 m spatial resolution digital elevation model.
[d] CanCoast: A National-scale Framework for Characterising Canada's Marine Coasts, 2013. 1 km spatial resolution.
[e] Sea Level Rise in the Coastal Waters of Washington State, 2008. Approximately 8–11 kms spatial resolution.
[f] 30 m spatial resolution.

$$CVI = \sqrt{\frac{a^1 \times a^2 \times a^3 \times \ldots \times a^n}{n}}$$

Fourth, the total range of computed values was divided into normal distribution quantiles, providing four range groups. These groups were assigned to very low, low, medium and high categories. The four range groups and corresponding categorical groups for both indices are provided in the (Appendix 1 and 2). And lastly, the spatially linked data were mapped using Geographic Information Systems (GIS).

The CVI methodology has been used in many other studies investigating environmental vulnerability and sensitivity such as Shaw et al. (1998), Gornitz (1991), Gornitz et al. (1992, 1994) as well as Thieler and Hammar-Klose (1999) but it has not been applied to the CGI coastal protection research.

4.4. Synthesizing the indices

After the CGI coastal protection and vulnerability indices were created, computed, and mapped, they were synthesized using a 2 × 2 matrix (Table 2). CGIs with low coastal protection benefits and high vulnerability; low coastal protection benefits and low vulnerability, high coastal protection benefits and high vulnerability, and high coastal protection benefits and low vulnerability were grouped. The spatially linked data were mapped using GIS.

Table 2
CGI typology matrix.

		CGI Coastal Protection Benefits	
		Very low/Low	High/Medium
CGI Vulnerability	Very low/Low	*Type* – 2	*Type* – 4
	High/Medium	*Type* – 1	*Type* – 3

5. Results

5.1. CGI coastal protection index

Quantitative and qualitative data on eight indicators were used to create the CGI coastal protection index. These indicators are the relief, coastal types, coastal vegetation, habitat zone, wave exposure, max. wave height, max. wave fetch, and coastal land use. Each variable for these indicators was assigned a rank from 1 to 5, where 1 represents very low, and 5 represent very high existing coastal protection benefits (Table 3). The coastal protection scale here does not represent an absolute very low to high protection benefits; rather, it represents the relative CGI protection benefits in the study area. In addition, these indicators assess the existing features of coasts, wave action, and land use, therefore the potential benefits claimed through this index is based on the existing conditions.

As discussed previously, the wave energy is attenuated through the surface roughness of the coasts and drag friction provided by the properties of coastal profile and coastal vegetation. The indicators that address this interaction through CGI properties and therefore used in the coastal protection index are the relief, coastal types, and coastal vegetation. Habitat zone indicator addresses the magnitude of this interaction. While wave indicators such as wave exposure, max. wave height, and max. wave fetch reflects the wave energy that is to be attenuated at the coast. Lastly, coastal land use reflects the extent of the development that needs protection.

The relief indicator in the CGI coastal protection index represents wave attenuation through coastal slope. Coops et al. (1996), Nicholls (2004), Wamsley et al. (2009) and Barbier et al. (2011), highlight the importance of coastal slope as a controlling factor for wave attenuation at coast. High relief increases the wave attenuation; therefore provides more coastal protection benefits. Coastal types attenuate wave energy through providing rough surfaces for the wave to go over (Möller, 2006; Loder et al., 2009; Wamsley et al., 2010; Möller et al., 2014). This indicator shows the dominant coastal types for the study area communities. Coasts with sand, gravel, and mudflats provide less roughness compared to estuaries, beaches, dunes and rocky platforms; therefore, provide less coastal protection. Surface roughness increases with sloped beaches, rocky beaches, and cliffed coasts. Human-made structures, although providing a degree of protection, often cause more damage due to their vertical alignment, wave over-topping, and parts of the structure becoming loose over time or with wave energy.

Coastal vegetation attenuates waves through drag friction the vegetation stems and leaves provide. Different vegetation types provide different drag friction because of density, length, and other structural differences (Koch et al., 2009; Anderson and Smith, 2014; Möller et al., 2014). Kelp forests are dense, and the vegetation has long stems, yet their interaction with waves are often limited because they are often located deeper than the wave break zones. As discussed in the literature review, seagrasses can effectively provide wave attenuation but their ability is often limited because of their short stems and less dense cover, and the wave height and the water depth ratio discussed previously (Mork, 1996). Salt marshes and dune vegetation provide higher degrees of wave attenuation because they have higher degrees of interaction with the waves (Bradley and Houser, 2009; Manca et al., 2012). The presence of multiple types of vegetation increases the drag friction at the coast and improves wave attenuation (Möller et al., 2014).

Habitat zone refers to the water depth that the dominant CGI is located. The literature suggests decreases in vegetation elevation or increases in depth results in less attenuation (Kobayashi et al., 1993; Nicholls, 2004; Möller, 2006; Loder et al., 2009; Anderson and Smith, 2014; John et al., 2015). CGIs at the inter-tidal and supra-tidal zones are more efficient in dissipating wave energy than CGIs at the sub-tidal zones due to the relationship between water depth and vegetation height.

Wave exposure indicates the frequency and intensity of wave action at the coast. This indicator refers to the tear stress CGI is exposed to.

Table 3
CGI coastal protection index.

Indicators	Very low	Low	Moderate	High	Very high
	1	2	3	4	5
Relief (m)	0–5	6–10	11–20	21–30	>30
Coastal types	Sand, gravel and mudflats	Human-made	Estuaries, beaches, and dunes	Rocky beaches	Rocky cliffs and platforms
Coastal vegetation	No vegetation	Kelp forests	Sea grasses	Marsh or dune veg.	Mixed vegetation
Habitat zone	Sub-tidal	Lower tide	Inter-tidal	Higher tide	Supra-tidal
Wave exposure	Exposed	Semi- exposed	Semi- protected	Protected	Very- protected
Max. wave height (m)	> 6.1	5.1–6.0	4.1–5.0	2.1–4.0	< 2.0
Max. fetch (km)	> 200	200–150	150–100	100–50	< 50
Coastal land use	Mostly gray	Mixed green and gray (commercial)	Mixed green and gray (residential)	Mostly green with agriculture	Mostly green

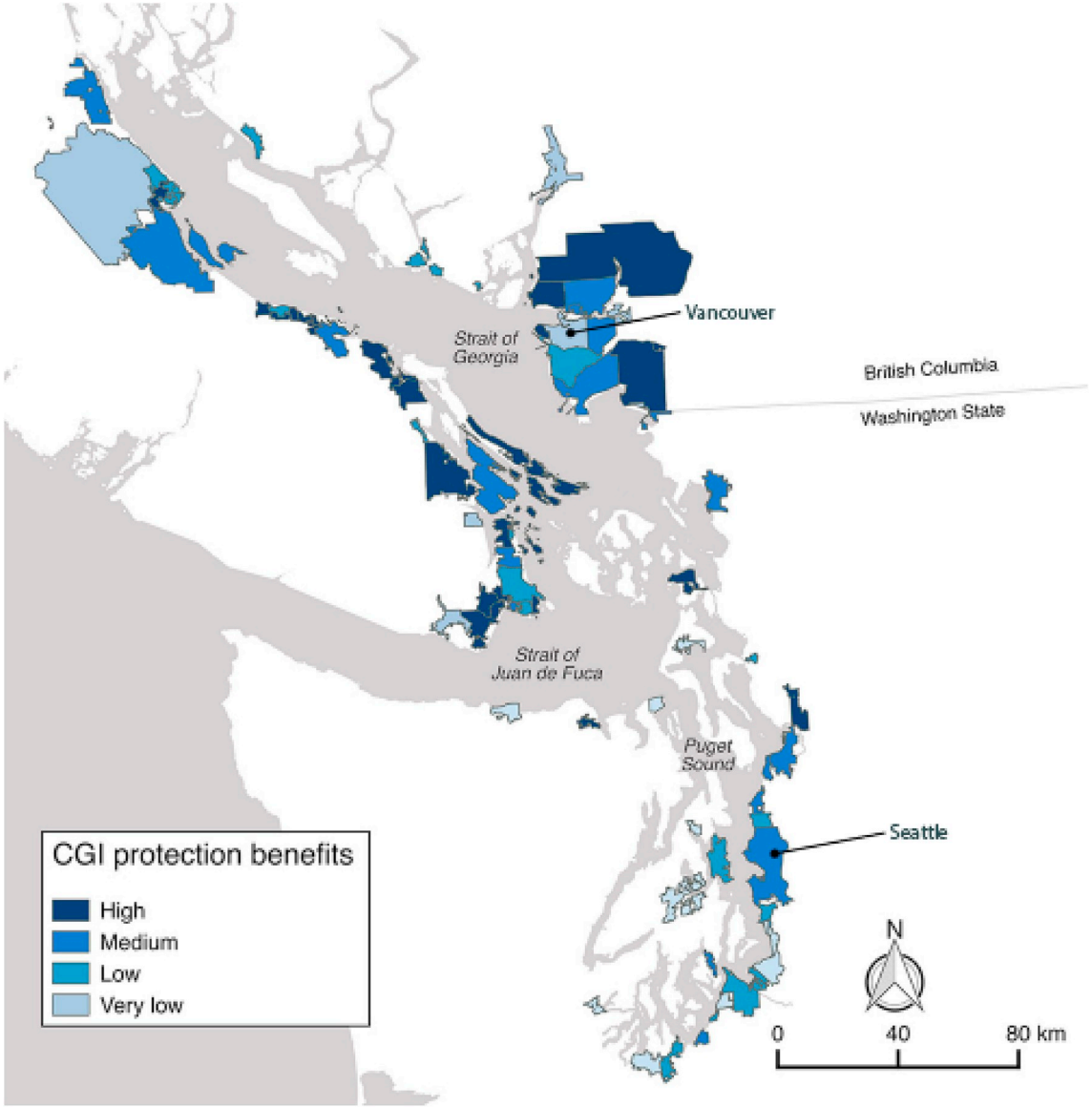

Fig. 3. Distibution of the CGI coastal protection benefits in the Salish Sea.

When the wave exposure increases, CGI's coastal protection benefits decrease. The maximum wave height indicator refers to the one-year highest wave height. The literature suggests that CGI is more effective in dampening the energy of small (0–2 m) to moderate height waves (2–4 m) (Wamsley et al., 2010; Duarte et al., 2013; Möller et al., 2014; John et al., 2015). Therefore increases in wave height lower CGI's coastal protection benefits. The maximum wave fetch indicator refers to the water surface area available for the wind to form waves. High wave fetch indicates higher and stronger waves (Bradley and Houser, 2009; Shepard et al., 2011), therefore reduces CGI's coastal protection benefits.

Lastly, the coastal land use indicates the extent of development at the coast that is at risk and needs protection. More development and infrastructure at coast increases the assets that are exposed to flooding whereas green and agricultural lands reduce the exposure and can further help CGI with attenuating wave energy and absorbing floodwater.

Based on this classification, CGI's coastal protection benefits are expected to be high where the coastal relief is high; the coastline consists of material that provides high roughness, and vegetation that attenuates wave energy; the habitat locates in the higher sections of the tidal range; wave exposure, wave height and fetch are low; and the land use at the coast consists mostly of green spaces. After the indicators were ranked and applied to the study area communities, the CGI coastal protection benefits index was computed and mapped (Fig. 3).

Fig. 3 shows that the distribution of CGI's coastal protection benefits is not homogeneous among the Salish Sea communities. The CGI in British Columbia has higher coastal protection benefits in general than the CGI in Washington State. CGI in 59% of the communities in BC and 37% of the communities in WA have medium to high coastal protection benefits. This is partially the result of the more dense and intensive occupation of the coastal areas in Washington State, which impacts the coastal types and coastal land use indicators. Approximately 17% of the total Washington State coastline is hardened with human-made structures (Gittman et al., 2015), whereas only about 3% of the British Columbia coastline has human-made structures, reflecting the differences in degree of human intervention in both coastal areas.

Examining Fig. 3 shows some interesting patterns in the region. For example, CGIs in big urban centers such as Vancouver, Seattle, Victoria, and Tacoma have different coastal protection benefits: very low, medium, low and high, respectively. The results of the coastal protection index show that even in communities with extensive areas of CGIs such as Squamish and Port Townsend, the implications of high wave fetch, height and exposure reduces CGI's coastal protection benefits

(Appendix Appendix 1). Similarly, in communities with low wave exposure such as Poulsbo, coastal types undermines the role of the CGI in providing coastal protection benefits.

Coastal protection benefits of CGI is one part of identifying areas with the highest potential coastal protection benefits. As mentioned in the previous sections, the vulnerability of CGI to changes in the environment needs to be considered as well.

5.2. CGI vulnerability index

Quantitative and qualitative data on seven indicators were used to create the CGI vulnerability index. These indicators are the relief, tidal range, habitat zone, sea level change, erosion change, wave exposure, and coastal land use. Each variable is assigned a rank from 1 to 5. Different from the CGI coastal protection index, here 1 represents very low, which is a positive construct and 5 represent very high existing vulnerability of CGI (Table 4). The vulnerability scale also does not represent an absolute very low to high vulnerability; rather it represents the relative CGI vulnerability in the study area.

Table 4
CGI vulnerability index.

Indicators	Very low	Low	Moderate	High	Very high
	1	2	3	4	5
Relief (m)	>30	21–30	11–20	6–10	0–5
Tidal range	>6.0	4.1–6.0	2.0–4.0	0.5–1.9	<0.50
Habitat zone	Supra-tidal	Higher tide	Inter-tidal	Lower tide	Sub-tidal
Sea level change (cm/100 years)	< −50	−50 to −20	−19 to +20	21 to 40	>40
Erosion change (m/y)	> +0.1	0	−0.1 to −0.5	−0.6 to −1.0	> −1.0
Wave exposure	Very protected	Protected	Semi- protected	Semi- exposed	Exposed
Coastal land use	Mostly green	Mostly green with agriculture	Mixed green and gray (residential)	Mixed green and gray (commercial)	Mostly gray

It has been discussed in the literature review section that factors such as coastal characteristics, coastal land use, and risks induced by climate change such as sea level rise (Duarte et al., 2013) are associated with CGI vulnerability. The indicators that address the coastal characteristics factors are the relief, tidal range, and habitat zone. Sea level rise, erosion and wave exposure indicators reflect the risks induced by climate change. The coastal land use reflects the intensity of the development at the coast which limits the amount of space CGIs have to migrate upland.

The relief indicator was used in the coastal protection index to reflect the slope and steepness of the coastal areas, which can help to attenuate wave energy. In the vulnerability index, the relief indicator reflects inundation risks throughout coastal slope. Low relief indicates larger areas with low elevation that is under inundation risk, therefore increases the vulnerability. The tidal range indicator shows the zone of the coast that is frequently inundated. It impacts the habitat zone and sediment deposition zone at coasts. The literature suggests that vegetation at the meso and macro-tidal range can accrete and deal with rising sea levels better due to the availability of this sediment deposition zone (Morris et al., 2002; Fitzgerald et al., 2008; Craft et al., 2009). The habitat zone indicator is related to the zone CGIs are in the tidal range. CGIs at the lower tidal zones are more vulnerable to the changing conditions because of the availability of the sediments throughout the tidal range is lower in the lower-tidal zones (Craft et al., 2009; Kirwan and Temmerman, 2009; Davidson-Arnott, 2010).

The sea level change indicator shows the changes in the water levels over the past 100 years. It includes sea level rise and vertical land movement adjustments. The negative values indicate land uplift, thus decrease in the sea levels, where the positive values indicate increases in the sea levels. Many studies discussed in the literature review section suggested that rapid rates of sea level rise will likely to cause CGI drowning (Feagin et al., 2005; Kirwan and Temmerman, 2009; Kirwan et al., 2010; Mariotti and Carr, 2014). The erosion change indicator refers to the stability of coastlines. Accretion is one of the most critical mechanisms CGIs use to deal with environmental stressors such as rising water levels (Feagin et al., 2015). The positive values indicate accretion, therefore low CGI vulnerability where the negative values indicate coastal erosion, thus high vulnerability. The wave exposure indicator in the CGI vulnerability index refers to the frequency and duration of inundation. High wave exposure can result in the loss of CGI due to tear stress, therefore increases vulnerability (Gedan et al., 2010).

The coastal land use indicator in the vulnerability index reflects the human development and activities at the coast that can confine CGI to a small zone, affecting its ability to move and adapt to changing conditions (Feagin et al., 2009). Greener, less developed coastal areas provide more room for CGI to migrate upland, therefore reduce CGI vulnerability. Gray and densely developed coastal areas create a 'coastal squeeze' (Osland et al., 2015; Kirwan et al., 2016), therefore increase CGI vulnerability.

Based on this classification, CGI's vulnerability is expected to be high if the coastal relief and tidal range are low; the habitat is located at the low parts of the tidal range; sea level change over the 100 years is high; the coast is erosional and exposed to high wave action; and land use at the coast is densely occupied with mostly of commercial and residential structures. After the indicators were ranked and applied to the study area communities, the CGI vulnerability index was computed and mapped (Fig. 4).

Fig. 4 shows that the distribution of CGI vulnerability also varies significantly in the Salish Sea. CGI in British Columbia is less vulnerable in general than the CGI in Washington State. CGI in 61% of the communities in BC and 33% of the communities in WA have low to very low vulnerability to changing environmental conditions. Relatively lower relief values of Washington State communities have a significant contribution to higher CGI vulnerability. Besides, higher rates of net sea level rise in Washington State, which is mainly due to the subsidence of the land, contributes to the CGI vulnerability. Moreover, the most developed and dense coastline of Washington State also increases the vulnerability of CGI.

Examining Fig. 4 also shows some interesting patterns in the region. Amongst the large urban centers, the CGI in Vancouver and Seattle have a high and medium vulnerability, respectively. CGI vulnerability in Vancouver is due to tidal range, wave exposure, and coastal land use, while in Seattle CGI vulnerability is caused by sea level rise and coastal land use. In other large urban centers such as Victoria and Tacoma, CGI has a low vulnerability (Appendix Appendix 2).

5.3. Synthesizing the indices

The results of the CGI coastal protection and vulnerability indices were synthesized to develop CGI types in the region. A 2 × 2 matrix (Table 2) was used to organize the categorical groups into CGI types. Four main CGI types were defined and their descriptions are provided as follows.

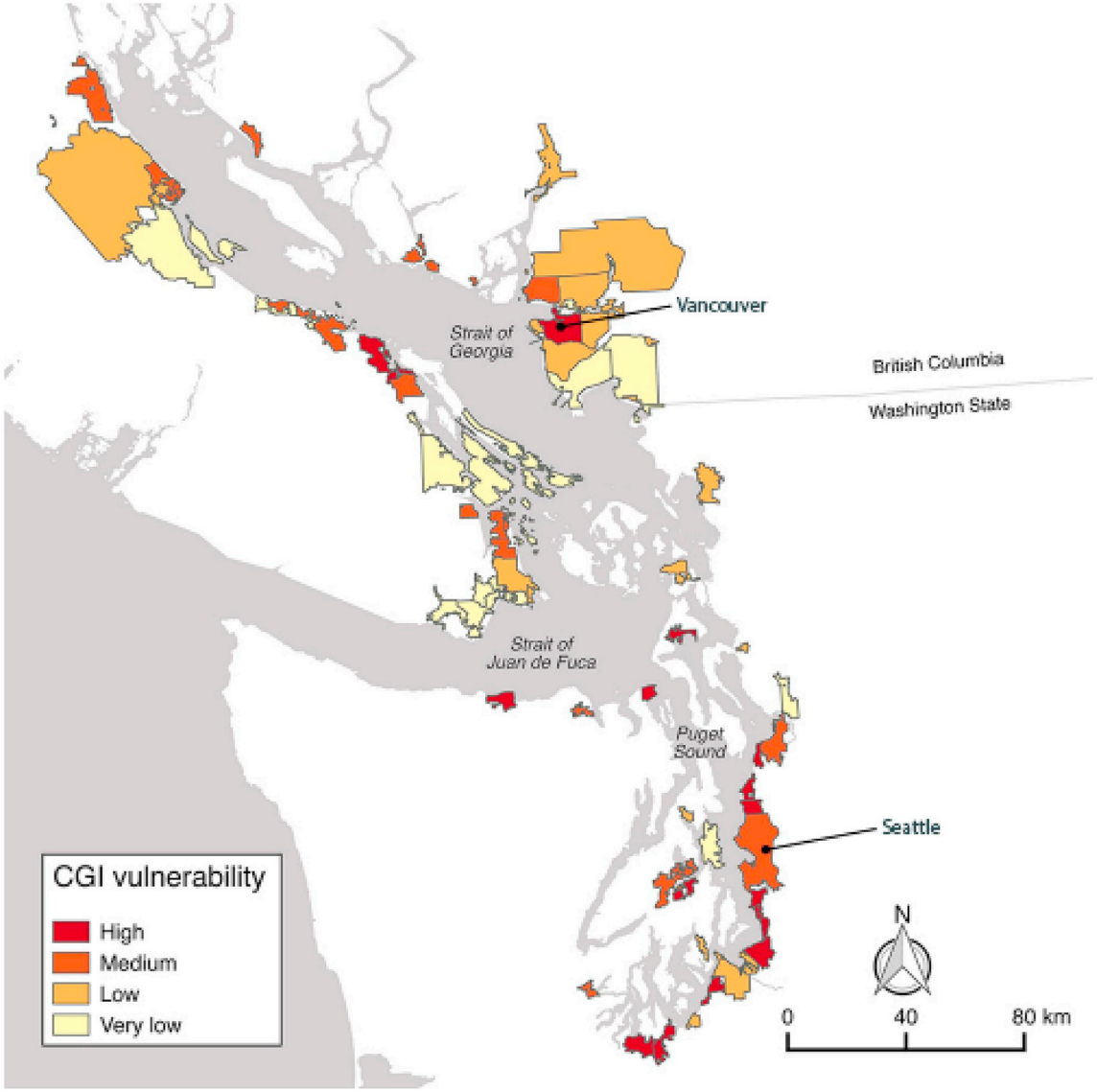

Fig. 4. Distibution of the CGI vulnerability in the Salish Sea.

- Type 1: CGI vulnerability is high, and coastal protection benefits are low.

The Type 1 CGI can be defined as the worst type CGI in the group. CGI may not be the best course of coastal protection and climate change adaptation action for the communities in the Type 1 zone. Rather, hybrid uses of hard structures and CGIs can be explored. Where applicable, adjusting the hard structures in a way to accommodate new CGI production can help to utilize other benefits of CGI other than coastal protection (i.e., adding texture to concrete seawalls can foster vegetation and oyster population). Also, Type 1 communities can focus on limiting coastal development to non-essential uses.

- Type 2: CGI vulnerability is low but coastal protection benefits are low as well.

The communities in the Type 2 zone have low potential to utilize their CGI. Therefore, they can explore ways to increase their CGI coastal protection benefits since the CGI vulnerability is low. These communities can focus their efforts on actions such as rehabilitating coastal vegetation or creating new habitats in the riparian areas to increase coastal protection opportunities. Where there are already hard protection structures, the hybrid uses of CGI and adjusting existing structures to allow the creation of new CGI can be explored.

- Type 3: CGI vulnerability is high, but coastal protection benefits are high as well.

The communities in the Type 3 zone have high potential to utilize their CGI, but their efforts should focus more on reducing the CGI vulnerability. This could be done by limiting land use and developments and removing barriers at the coast to ensure that CGI has space to move upland and adjust to changes. Also, beach nourishment and other rehabilitation strategies such as replanting vegetation can be used to reduce CGI vulnerability. Site-specific investigations can look into replacing existing hard structures with CGI, and where it is not safe or feasible to replace hard structures, hybrid uses of CGIs and hard structures can be explored.

- Type 4: CGI vulnerability is low, and protection benefits are high.

Type 4 CGI can be defined as the best type of CGI in the group. The communities in the Type 4 zone have the greatest potential to utilize their CGI for coastal protection as the CGI vulnerability is low. These

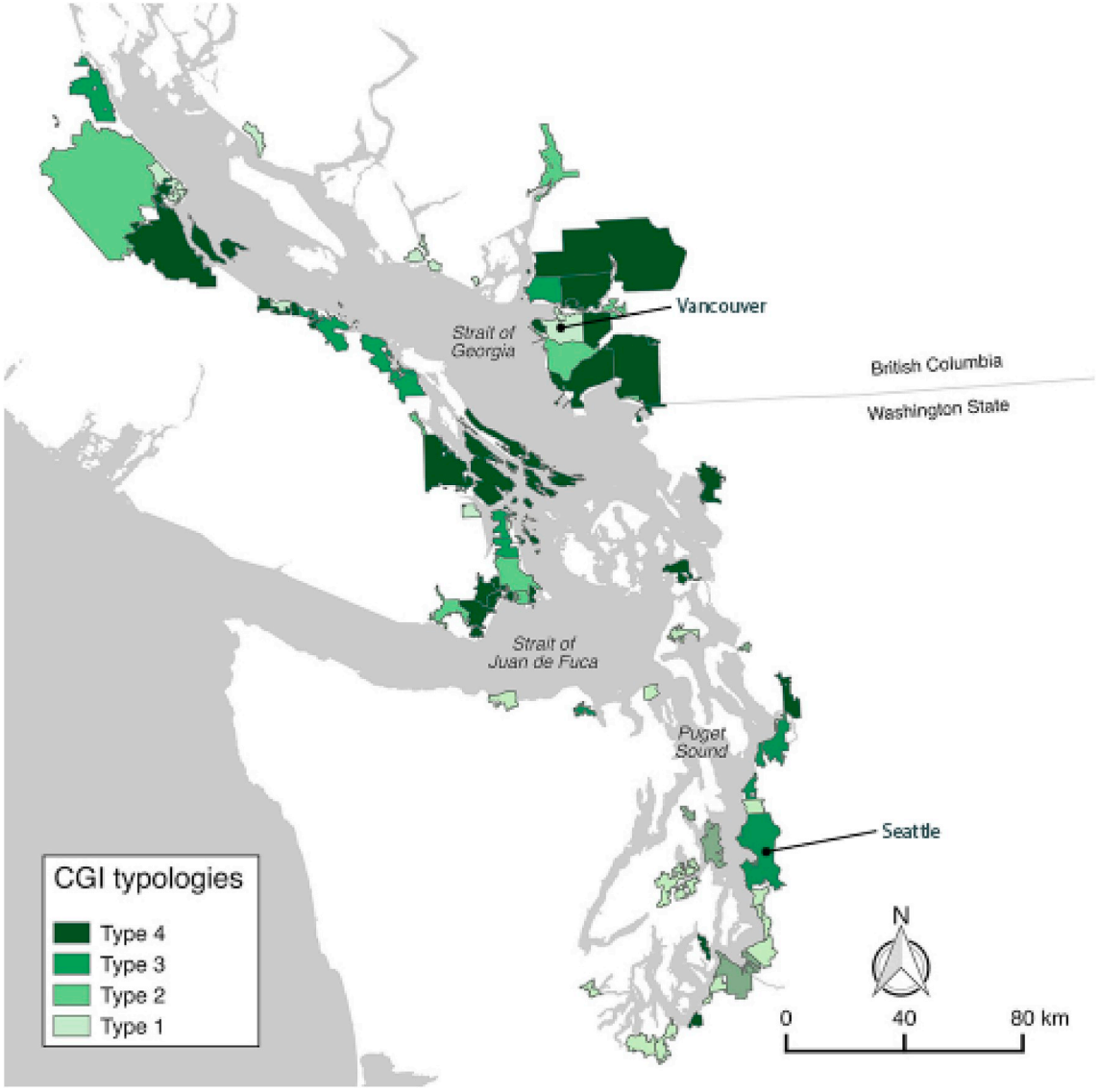

Fig. 5. Distribution of the CGI types in the Salish Sea.

communities can focus their efforts into site-specific investigations to outline how and where in their coastlines CGIs can be incorporated in the community's sea level rise adaptation strategies and flood management practices. The communities in the Type 4 zone can undertake habitat enhancement, hard structure removal, and CGI replacement projects. Also, they can hold public workshops to inform waterfront homeowners on how to implement nature-based solutions in their properties.

Fig. 5 shows that the big population centers in British Columbia, such as Vancouver, Richmond, Victoria, and Saanich fall under Type 1 and Type 2 CGI, suggesting CGI may not be the most appropriate tool for coastal protection in these communities. Hybrid CGI solutions with hard structures can be used to mitigate the environmental impacts of hards structures. Communities surrounding the large urban centers mostly have Type 3 and Type 4 CGI in British Columbia, indicating that the British Columbia communities in the Salish Sea region have high potential to utilize CGI for coastal protection. About 59% of the communities in British Columbia are either Type 3 (18%) or Type 4 (41%). On the other hand, only about 36% of the communities in the Washington States fall under Type 3 (16%) or Type 4 (20%). Communities in Washington State, particularly in the south of the Puget Sound, have low potential to utilize their CGI. Unlike in Vancouver, the CGI in Seattle falls under Type 3 zone, and communities surrounding Seattle have lower CGI potentials.

6. Discussion

Hard structures have been the preferred coastal protection method for centuries due to several important reasons. First and foremost, they protect private and public properties, and sustain the ownership, development, and occupation of the land (Tyler, 2016). Second, Klein et al. (2001) and French (2006) suggest that the more tangible and easy to visualize the nature of hard structures makes them more appealing to decision makers. Third, compared to CGIs, the implementation of Traditional Hard Sturctures (THSs) often takes considerably less land space. Considering the high land values in coastal areas and the need and desire to utilize these valuable areas, THSs can be implemented much more easily than their CGI counterparts in “in intertidal and shallow subtidal environments” (2005, pg.1074). Yet, hard structures provide a false sense of security as their vertical interaction with waves creates wave over-topping, resulting in damage and flooding. The static and maladaptive nature of hard structures contributes to their structural inefficiency for coastal protection. The costs associated with the implementation and maintenance of hard structures create a significant

economic burden on communities. In addition, the environmental implications of hard structures on coastal processes, ecosystem health and integrity, and wildlife have been significant. There have been growing concerns over hard structures' economic, physical and environmental implications.

As an alternative, CGI has been considered as a viable coastal protection method for the last few decades, and a growing number of studies have provided evidence of CGI's coastal protection benefits. It should be noted here, however, that most of these studies were conducted before the use of natural assets as coastal protection methods were called CGI. These studies have paved the way to wide-ranging consideration of CGIs both in research and practice. Especially after disasters such as Hurricanes Katrina and Sandy, there has been a growing interest from governments to invest in nature-based coastal protection methods (Sutton-Grier et al., 2015). However, even though CGI has started to gain popularity as a coastal protection method in the literature, compared to the hard structures the extent of CGI benefits in different environmental conditions has not yet been well established. Also, how vulnerability can limit, if not diminish CGI coastal protection benefits has not been studied.

Increasingly, federal, state/provincial and regional government documents on sea level rise adaptation and coastal flood management, in general, have started to include the use of CGI rather than or in addition to traditional hard structures. These high-level guidance documents do not always foster the implementation of CGI because they do not outline where CGI can be potentially useful in providing coastal protection benefits and where it cannot. This study fills this gap by providing a methodological approach and a regional level assessment of CGI coastal protection benefits and vulnerability. This paper uses the 74 most populated coastal communities in the Salish Sea region to demonstrate the methodological framework. The contributions of this study can be summarized in four main points.

First, investigating where CGI can yield high coastal protection benefits while considering its vulnerability is a novel approach. Traditional CGI studies study specific sites to estimate coastal protection benefits of the CGI at that location. This approach is useful to set an understanding of the rate of wave attenuation or accretion that can be achieved by CGI in that specific environment. Most of these studies often disregard the vulnerability CGI may be experiencing or could experience in future, yet this vulnerability can drastically alter potential coastal protection benefits. Some of the indicators were used in both of the indices, because of their influence on CGI's coastal protection benefits and its vulnerability. Including a vulnerability framework helps to identify CGI that has potential to provide coastal protection benefits but is facing high vulnerability. For example, communities with Type 3 CGI are characterized as where the potential CGI coastal protection benefits are high, but vulnerability is high as well. These communities should use caution in determining where to implement CGI, and whether they can provide environmental conditions or interventions that reduce CGI vulnerability. A misplaced CGI for coastal protection purposes can be a costly mistake communities should avoid.

Second, besides the CGI typologies, the indices developed in this study can be used independently and still be useful. The methodology and the indices used in this study can be used to investigate CGI in multiple scales, from an individual property level to a national level, and in various coastal areas around the world. The indicators of the indices can be customized to reflect specific features of different study areas. For example, mangroves and/or reef systems can be incorporated in the coastal vegetation indicator, if the study area is in the tropical and the lower latitudes of the sub-tropical coastlines. In addition, more indicators can be added to the indices, if data is available. For example, sediment concentration indicator can be included in the vulnerability index, since it has been deemed very important for determining CGI vulnerability but was not included in this study due to missing data.

Third, the results of a regional level CGI assessment can be a valuable contribution for multiple levels of governance in the region. The relative nature of scale used in both indices and the final synthesis of the indices into CGI types could inform management and operational issues, and resource and funding allocation. These actions can aim to reduce vulnerability and increase coastal protection benefits through projects such as coastal rehabilitation, beach nourishment, and others. This level of assessment would also help to prioritize such decisions by highlighting areas with high CGI coastal protection benefits but high vulnerability (Type 3), or areas with low CGI vulnerability but low coastal protection benefits (Type 2). Moreover, a regional level CGI assessment can help protect essential coastal habitat in some places and can help the creation of new ones in others, therefore contributes to the overall regional environmental sustainability. It should be noted that the management and operational recommendations provided in this study are preliminary. More detailed studies would be needed to explore specific prioritization and conservation and rehabilitation actions.

Fourth, this study can help regional knowledge sharing and collaboration among communities. The study area consists of two countries and state/provincial governments, making it difficult to implement similar measures. However, communities in similar CGI typologies can nevertheless share knowledge, resources and best practices on their coastal flood management strategies and sea level rise adaptation programs. For example, Type 1 and Type 3 communities can learn ways to reduce CGI vulnerability from Type 2 and Type 4 communities. Information sharing on habitat rehabilitation or relocation to change the existing habitat zone, beach nourishment and planting more vegetation to reduce erosion, and land use practices to ensure suitable habitat for CGI can be beneficial for communities seeking to reduce their CGI vulnerability. Besides, neighboring communities with similar CGI typologies can collaborate on projects. Especially for smaller communities with limited resources, knowledge sharing and opportunities for collaboration can provide various economic, social and institutional benefits.

Besides its contributions, the limitations of this research can be summarized as follows. It has been argued that a significant contribution of this research is the consideration of CGI vulnerability while investigating its coastal protection benefits. However, this work does not explain the extent of the vulnerability impact on the protection benefits, nor the magnitude of the impact. The vulnerability of CGI can have distinct manifestations depending on the existing natural and built environment conditions, and the type(s) of CGI present. Therefore, CGI vulnerability can have various implications for the coastal protection benefits of CGI in different locations. Investigation of the extent and magnitude of CGI vulnerability on coastal protection benefits was not included in the scope of this study. In addition, the range of the indicator values and therefore the findings of this study should be considered within the geographical context of the study area. Indicator values and ranges would need to be adjusted for regions with different geomorphological conditions and characteristics, such as tropical regions.

The temporal functions of the CGI's coastal protection benefits and vulnerability were also not included in the study. Seasons influence the CGI's character (by changing the CGI density, cover, and length), wave characteristics (by altering the frequency, intensity, and duration of the wave events), and sediment rates (by changing currents and tides). Unfortunately, temporal data on the indicators used in this study were not available, therefore, were not included in the scope of this study.

Besides, the data availability and gaps, common issues on indicator-based models, have restricted the indicators used in the creation of the indices. Amongst the 13-parameter themes identified, only eight themes and 11 correspondent indicators were used in this research. Some important themes such as sedimentation or CGI cover were not included in the analysis because of missing or incomplete data. This limitation has direct impacts on the results as the number of indicators and values of indicators are properties of the equation used to compute the indices. However, it should be noted here that Gornitz et al. (1994) suggested that the formula used in this paper was relatively insensitive to

variations and was able to produce useable results when changes occur in the variables.

Lastly, the benefits of a regional level CGI assessment were discussed above. It is important to note that the high-level nature of regional assessments makes it challenging to capture variations at the local level. While there is consistent evidence in the literature on the positive coastal protection role of CGI, for a given environmental, morphologic and biological condition, CGI may not be the best course of action (Wamsley et al., 2010) for every segment of a community's coastline. More detailed studies are needed in order to assess the localities and highlight where in each community CGI can yield the highest protection benefits.

7. Conclusion

This study develops provides a methodology to identify areas where CGI has more significant (or less significant) promise for coastal protection. It does so by incorporating potential coastal protection benefits and vulnerability to changing environmental conditions, using an indicator-based approach. This study provides a methodology that could help regional and local governments in decision-making for flood management and sea level rise adaptation. Moreover, it can facilitate knowledge sharing and collaboration within a region.

The methodological approach presented in this study and the findings of the research highlight the need for further research. A potential area of research includes identifying alternative approaches to indicator-based methods. Lying between policy, practice, and research what other methods can produce outcomes that are easy to understand and implement? In addition, more research is needed to deal with data gaps effectively. Moreover, comparative studies investigating the results of different computation methods can help in understanding both the shortcomings and benefits of the CVI methodology used in this paper. Another research area includes the local level application of the methods and indices of this work. For example, can a similar approach be used in the local scale to identify areas of highest CGI potential in a community's coastline? Advancing the CGI research in various scales and perspectives would be valuable for its implementation for coastal protection.

Disclosure statement

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Appendix

Appendix 1

Table 5
CGI coastal protection index indicator values, scores and classes. Lowest score: 4.74, Highest score: 82.16 Very low: 4.74–23.91; low: 23.91–36.16; medium: 36.16–51.55; high: 51.55–82.16

CSDUID	Community	Relief	C.types	C.vege.	W.exp.	W.hgt.	W.fet.	H.zone	Land use	Index	Classes
5929005	Gibsons	5	1	3	3	3	4	3	3	24.65	low
5919049	Cowichan Valley C	3	1	5	3	3	n/a	3	4	15.21	v_low
5917042	Metchosin	5	5	4	2	3	4	3	4	60.00	high
5917029	Capital G	5	4	5	3	3	3	3	4	63.64	high
5921030	Nanaimo E	5	4	5	3	3	1	3	4	36.74	med.
5926021	Comox Valley A	5	1	5	4	3	3	3	5	41.08	med.
5921010	Nanaimo A	3	4	5	3	3	5	4	4	73.48	high
5926022	Comox Valley B	5	1	5	3	3	4	3	3	31.82	low
5921034	Nanaimo G	5	3	5	4	3	4	3	5	82.16	high
5919021	Ladysmith	5	1	4	4	3	5	4	1	24.49	low
5926024	Comox Valley C	5	1	4	3	3	n/a	3	4	17.57	v_low
5921023	Qualicum Beach	5	1	3	3	3	4	3	3	24.65	low
5929011	Sechelt	5	5	5	3	3	1	3	3	35.58	low
5917047	View Royal	5	4	4	4	3	5	3	3	73.48	high
5917027	Capital F	5	4	5	3	3	n/a	3	4	39.28	med.
5917005	North Saanich	3	4	5	4	3	4	3	3	56.92	high
5917010	Sidney	3	1	5	3	3	4	4	3	28.46	low
5917052	Sooke	5	1	4	4	1	1	3	5	12.25	v_low
5921018	Parksville	5	3	5	4	3	4	3	3	63.64	high
5915020	Greater Vancouver A	5	5	4	4	3	3	3	3	63.64	high
5927008	Powell River	5	1	3	3	3	5	3	3	27.56	low
5926005	Comox	5	3	5	3	3	n/a	3	3	29.46	low
5917015	Central Saanich	3	1	5	4	3	5	3	4	36.74	med.
5917041	Colwood	5	3	4	4	3	4	5	3	73.48	high
5917040	Esquimalt	5	2	4	4	3	5	5	1	38.73	med.
5931006	Squamish	5	2	4	4	1	2	3	3	18.97	v_low
5917030	Oak Bay	5	4	5	3	3	4	3	3	63.64	high
5915007	White Rock	5	1	4	3	1	5	4	3	21.21	v_low
5926010	Courtenay	5	3	4	4	3	4	3	3	56.92	high
5919008	North Cowichan	5	3	5	4	1	5	3	5	53.03	high
5917044	Langford	5	3	5	5	1	5	5	3	59.29	high
5924034	Campbell River	5	3	5	3	3	3	3	3	47.73	med.
5915043	Port Moody	5	1	5	4	1	5	3	3	23.72	v_low
5915055	West Vancouver	5	5	3	3	3	4	3	3	55.11	high
5915051	North Vancouver	5	2	3	4	3	5	5	2	47.43	med.
5917034	Victoria	5	2	4	2	3	4	5	1	24.49	low

(*continued on next page*)

Table 5 (*continued*)

CSDUID	Community	Relief	C.types	C.vege.	W.exp.	W.hgt.	W.fet.	H.zone	Land use	Index	Classes
5921007	Nanaimo	3	4	5	4	3	4	3	3	56.92	high
5915046	D. North Vancouver	5	2	3	4	3	4	3	3	40.25	med.
5915011	Delta	5	3	5	4	1	3	4	4	42.43	med.
5917021	Saanich	5	1	5	3	3	5	3	3	35.58	low
5915015	Richmond	5	2	5	4	1	3	4	2	24.49	low
5915025	Burnaby	5	1	5	4	3	4	3	3	36.74	med.
5915004	Surrey	5	3	5	4	1	5	4	4	54.77	high
5915022	Vancouver	5	2	5	2	3	4	3	1	21.21	v_low
5306505	Blaine	3	1	5	4	3	4	3	5	36.74	med.
5367770	Steilacoom	3	3	5	3	2	5	3	2	31.82	low
5367455	Stanwood	2	3	4	5	2	5	5	1	27.39	low
5349415	Normandy Park	3	1	3	3	2	5	3	3	17.43	v_low
5363385	Sequim	4	3	5	4	2	5	3	3	51.96	high
5326735	Gig Harbor	3	3	5	5	2	5	3	3	50.31	med.
5318965	DuPont	4	3	4	3	2	5	5	2	42.43	med.
5355855	Port Townsend	3	1	4	2	4	1	3	1	6.00	v_low
5355995	Poulsbo	3	1	5	5	1	5	3	3	20.54	v_low
5363735	Shelton	3	2	4	4	1	5	5	1	17.32	v_low
5355785	Port Orchard	3	1	1	4	1	5	3	1	4.74	v_low
5301990	Anacortes	5	2	5	4	5	4	3	2	54.77	high
5355365	Port Angeles	3	3	4	3	5	1	3	1	14.23	v_low
5347735	Mukilteo	4	3	4	3	3	5	3	3	49.30	med.
5350360	Oak Harbor	2	1	5	4	2	5	3	1	12.25	v_low
5303736	Bainbridge Island	5	1	5	4	2	5	3	3	33.54	low
5317635	Des Moines	4	1	3	3	2	5	3	3	20.12	v_low
5373465	University Place	4	3	4	3	2	5	3	1	23.24	v_low
5308850	Burien	4	1	3	3	3	5	3	3	24.65	low
5307695	Bremerton	5	3	5	4	1	5	3	1	23.72	v_low
5320750	Edmonds	4	3	3	3	3	5	3	3	42.69	med.
5336745	Lacey	2	3	5	3	2	5	3	3	31.82	low
5351300	Olympia	3	1	5	4	2	5	3	2	21.21	v_low
5363960	Shoreline	4	1	4	3	3	4	3	3	25.46	low
5343955	Marysville	3	3	5	5	3	5	5	2	64.95	high
5305280	Bellingham	5	2	5	4	3	5	3	2	47.43	med.
5323515	Federal Way	4	1	3	3	2	5	3	3	20.12	v_low
5322640	Everett	4	2	5	5	3	5	3	2	47.43	med.
5370000	Tacoma	4	2	4	5	2	5	3	2	34.64	low
5363000	Seattle	5	2	5	3	4	5	3	2	47.43	med.

Appendix 2

Table 6
CGI vulnerability index indicator values, scores and classes. Lowest score: 3.21, highest score: 26.35 Very low: 3.21–8.85; low: 8.85–10.48; medium: 10.48–14.43; high: 14.43–26.35

CSDUID	Community	Relief	Sea level	Tidal rng.	Slope stab.	W.exp.	H.zone	Land use	Index	Classes
5929005	Gibsons	1	3	4	3	3	3	3	11.78	med.
5919049	Cowichan Valley C	3	3	3	3	3	3	2	14.43	med.
5917042	Metchosin	1	1	4	3	4	3	2	6.41	v_low
5917029	Capital G	1	3	3	3	3	3	2	8.33	v_low
5921030	Nanaimo E	1	4	4	3	3	3	2	11.11	med.
5926021	Comox Valley A	1	3	4	3	2	3	1	5.55	v_low
5921010	Nanaimo A	3	3	4	3	3	2	2	13.61	med.
5926022	Comox Valley B	1	3	4	3	3	3	3	11.78	med.
5921034	Nanaimo G	1	4	4	3	2	3	1	6.41	v_low
5919021	Ladysmith	1	3	3	3	2	2	5	8.78	v_low
5926024	Comox Valley C	1	3	4	3	3	3	2	9.62	low
5921023	Qualicum Beach	1	4	4	3	3	3	3	13.61	med.
5929011	Sechelt	1	3	4	3	3	3	3	11.78	med.
5917047	View Royal	1	3	3	3	2	3	3	8.33	v_low
5917027	Capital F	1	3	3	3	3	3	2	8.33	v_low
5917005	North Saanich	3	3	3	3	2	3	3	14.43	med.
5917010	Sidney	3	3	3	3	3	2	3	14.43	med.
5917052	Sooke	1	1	4	3	2	3	1	3.21	v_low
5921018	Parksville	1	4	4	3	2	3	3	11.11	med.
5915020	Greater Vancouver A	1	3	4	3	2	3	3	9.62	low
5927008	Powell River	1	3	4	3	3	3	3	11.78	med.
5926005	Comox	1	3	4	3	3	3	3	11.78	med.
5917015	Central Saanich	3	3	3	3	2	3	2	11.78	med.
5917041	Colwood	1	3	3	3	2	1	3	4.81	v_low
5917040	Esquimalt	1	3	3	3	2	1	5	6.21	v_low
5931006	Squamish	1	3	4	3	2	3	3	9.62	low

(*continued on next page*)

Table 6 (*continued*)

CSDUID	Community	Relief	Sea level	Tidal rng.	Slope stab.	W.exp.	H.zone	Land use	Index	Classes
5917030	Oak Bay	1	3	3	3	3	3	3	10.21	low
5915007	White Rock	1	3	4	3	3	2	3	9.62	low
5926010	Courtenay	1	3	4	3	2	3	3	9.62	low
5919008	North Cowichan	1	3	3	3	2	3	1	4.81	v_low
5917044	Langford	1	3	4	3	1	1	3	3.93	v_low
5924034	Campbell River	1	3	4	3	3	3	3	11.78	med.
5915043	Port Moody	1	3	4	3	2	3	3	9.62	low
5915055	West Vancouver	1	3	4	3	3	3	3	11.78	med.
5915051	North Vancouver	1	3	4	3	2	1	4	6.41	v_low
5917034	Victoria	1	3	3	3	4	1	5	8.78	v_low
5921007	Nanaimo	3	3	4	3	2	3	3	16.66	high
5915046	D. North Vancouver	1	3	4	3	2	3	3	9.62	low
5915011	Delta	1	3	4	3	2	2	2	6.41	v_low
5917021	Saanich	1	3	3	3	3	3	3	10.21	low
5915015	Richmond	1	3	4	3	2	2	4	9.07	low
5915025	Burnaby	1	3	4	3	2	3	3	9.62	low
5915004	Surrey	1	3	4	3	2	2	2	6.41	v_low
5915022	Vancouver	1	3	4	3	4	3	5	17.57	high
5306505	Blaine	3	4	2	3	2	3	1	7.86	v_low
5367770	Steilacoom	3	3	3	3	3	3	4	20.41	high
5367455	Stanwood	4	4	3	3	1	1	5	10.14	low
5349415	Normandy Park	3	4	3	3	3	3	3	20.41	high
5363385	Sequim	2	3	2	4.5	2	3	3	11.78	med.
5326735	Gig Harbor	3	3	3	3	1	3	3	10.21	low
5318965	DuPont	2	3	3	3	3	1	4	9.62	low
5355855	Port Townsend	3	3	2	4.5	4	3	5	26.35	high
5355995	Poulsbo	3	3	3	3	1	3	3	10.21	low
5363735	Shelton	3	3	3	3	2	1	5	10.76	med.
5355785	Port Orchard	3	3	3	3	2	3	5	18.63	high
5301990	Anacortes	1	4	2	3	2	3	4	9.07	low
5355365	Port Angeles	3	3	2	3	3	3	5	18.63	high
5347735	Mukilteo	2	4	3	3	3	3	3	16.66	high
5350360	Oak Harbor	4	4	3	3	2	3	5	24.84	high
5303736	Bainbridge Island	1	3	3	3	2	3	3	8.33	v_low
5317635	Des Moines	2	4	3	3	3	3	3	16.66	high
5373465	University Place	2	3	3	3	3	3	5	18.63	high
5308850	Burien	2	4	3	3	3	3	3	16.66	high
5307695	Bremerton	1	3	3	3	2	3	5	10.76	med.
5320750	Edmonds	2	4	3	3	3	3	3	16.66	high
5336745	Lacey	4	3	3	3	3	3	3	20.41	high
5351300	Olympia	3	3	3	3	2	3	4	16.66	high
5363960	Shoreline	2	4	3	3	3	3	3	16.66	high
5343955	Marysville	3	4	3	3	1	1	4	7.86	v_low
5305280	Bellingham	1	4	2	3	2	3	4	9.07	low
5323515	Federal Way	2	4	3	3	3	3	3	16.66	high
5322640	Everett	2	4	3	3	1	3	4	11.11	med.
5370000	Tacoma	2	3	3	3	1	3	4	9.62	low
5363000	Seattle	1	4	3	3	3	3	4	13.61	med.

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